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NSWCDD/TR-97/143

**COMPARISON OF DIVERGENCE MEASUREMENT
TECHNIQUES FOR OUTDOOR LASER DISPLAY
APPLICATIONS**

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FOREWORD

Since 1979, the Naval Surface Warfare Center Dahlgren Division (NSWCDD) has been the Navy's Technical Direction Agent (TDA) for laser safety and has provided technical assistance to Navy and Marine Corps range personnel, system developers, and system users. This report provides a comparison of methods used in measuring parameters of lasers to determine the divergence of outdoor laser systems.

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CONTENTS

<u>Section</u>	<u>Page</u>
1 INTRODUCTION	1
2 LASER BEAM DIVERGENCE.....	2
2.1 PURPOSE	2
2.2 EXPERIMENTAL BACKGROUND	2
2.3 MEASUREMENT TECHNIQUES FOR DETERMINING LASER BEAM DIVERGENCE.....	3
2.3.1 TWO-POINT APERTURE METHOD.....	3
2.3.2 LONG FOCAL LENGTH LENS AND SMALL APERTURE METHOD.....	4
2.3.3 KNIFE-EDGE TECHNIQUE.....	5
2.3.4 BEAM PROFILER METHOD	6
3 MEASUREMENT RESULTS.....	7
3.1 COMPARISON OF TECHNIQUES	7
4 REFERENCES	9
DISTRIBUTION	(1)

ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1 LASER BEAM GEOMETRY	2
2 MEASUREMENT POINT EXAMPLE	3
3 LONG FOCAL LENGTH LENS AND SMALL APERTURE METHOD SETUP	4
4 KNIFE-EDGE METHOD SETUP.....	5

TABLES

<u>Table</u>		<u>Page</u>
1	MEASUREMENT RESULTS.....	7
2	ADVANTAGES AND DISADVANTAGES OF TECHNIQUES.....	8

SECTION 1

INTRODUCTION

The Space and Naval Warfare Systems Command (SPAWAR), as the Navy's lead agency for laser safety, has established the Naval Surface Warfare Center Dahlgren Division (NSWCDD) as the Technical Direction Agent (TDA) for Navy and Marine Corps laser safety. Part of this responsibility includes the evaluation of lasers and laser systems used on Navy and Marine Corps installations for personnel hazards and the recommendation of measures designed to eliminate exposure of personnel to potentially hazardous optical radiation from these devices.

NSWCDD Code G71 evaluates many laser systems for laser hazards. The potential laser and ancillary hazards associated with the use of laser systems are evaluated, and recommendations are made to eliminate exposure of personnel to the potentially hazardous optical radiation from these devices. A number of measurement methods used to determine laser beam divergence involved in this type of evaluation are presented and compared in this report.

In recent years, an increasing number of pilots have been exposed to laser radiation while piloting aircraft. These exposures have typically resulted in glare or flashblindness, creating a potentially unsafe condition, especially during takeoffs and landings. In Biloxi, Mississippi, military pilots were illuminated by laser display systems. In Las Vegas, Nevada there have been over fifty reported incidents of pilot laser illumination. Because of the volume of incidents and the fact that McCarran Airport borders the Las Vegas strip, the Food and Drug Administration (FDA) imposed a moratorium on outdoor laser light shows in Las Vegas to prevent further incidents. The light show operators and the hotel managers wanted the light shows back on for advertising and entertainment purposes. However, prior to further operation, the Federal Aviation Administration (FAA), FDA, McCarran Airport, and the Las Vegas Police Department required that the light shows demonstrate proof of operation without the possibility of eye or flight hazards from laser exposures near the airport.

The FAA recently published an addendum to FAA order 7400.2D as interim guidance on laser exposure levels near airports. This and the previous events led to a request from the International Laser Display Association for several laser measurement teams to go to Las Vegas to perform divergence measurements on a number of light show lasers. The measurement teams included participants from the U. S. Navy, U. S. Army, U. S. Air Force, and Walt Disney World. Each team used a different technique to determine the divergence of light show lasers at the Las Vegas Hilton and the Luxor Hotel. The purpose of these measurements was to compare techniques and find the most practical method to determine beam divergence for laser safety calculations for a typical outdoor laser application.

SECTION 2

LASER BEAM DIVERGENCE

2.1 PURPOSE

The purpose of this experiment was to demonstrate several techniques for determining the divergence of lasers used in outdoor laser light shows and to find the most practical method to determine beam divergence for laser safety calculations for a typical outdoor application.

2.2 EXPERIMENTAL BACKGROUND

The divergence of a laser beam used in laser safety calculations is defined as the full angle of the beam spread measured between those points which include laser energy or irradiance equal to $1/e$ of the maximum value.¹ As a circular, Gaussian laser beam propagates through space, it produces a profile as shown in Figure 1. The beam diameter, D_L , is a function of range, r , from the exit port or beam waist and can be calculated as:

$$D_L = \sqrt{a^2 + r^2 \phi^2} \quad (1)$$

where a is the beam diameter (@ $1/e$ power points) at the exit port or beam waist and ϕ is the beam divergence (@ $1/e$ power points).

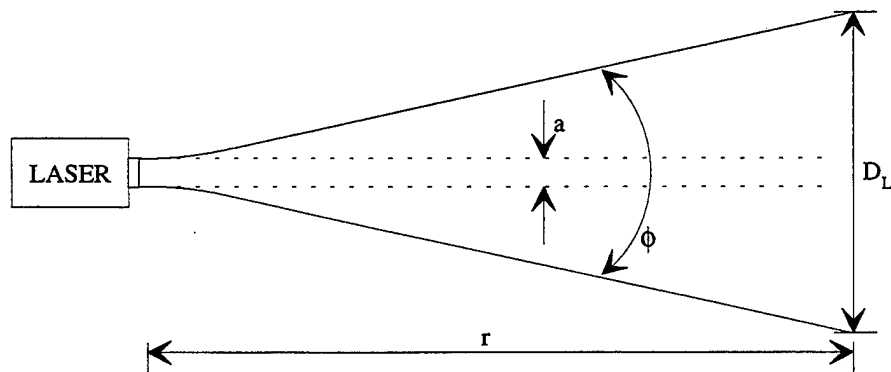


FIGURE 1. LASER BEAM GEOMETRY

2.3 MEASUREMENT TECHNIQUES FOR DETERMINING LASER BEAM DIVERGENCE

There are several techniques used to determine the divergence of a laser beam. Those done in this demonstration included the two-point aperture method, the long focal length lens and small aperture method, the knife-edge measurement method, and use of a beam profiling system.

2.3.1 Two-Point Aperture Method

Measurements to determine the divergence of a laser using the two-point aperture method require an optical detector, a variable aperture, a vernier caliper, and a tape measure. The total power and the power passing through an aperture smaller than the beam diameter at two points down range from the laser (as shown in Figure 2) must be measured.

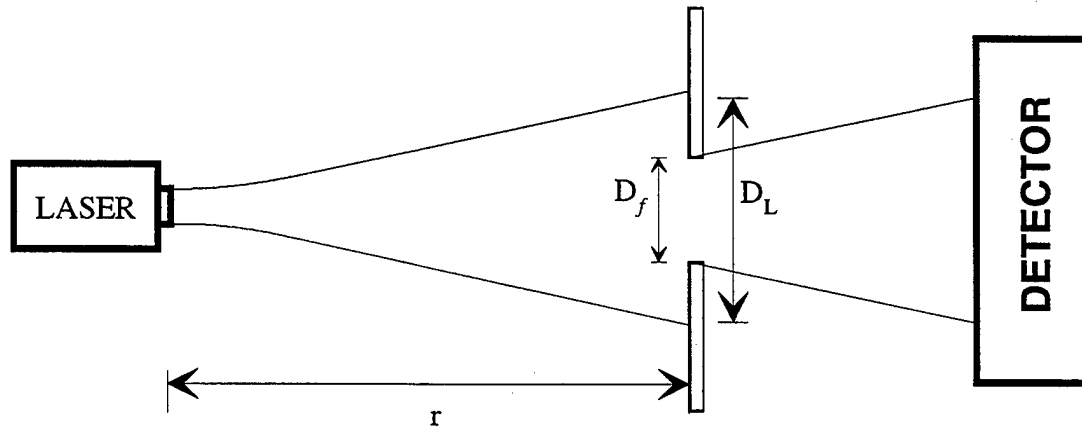


FIGURE 2. MEASUREMENT POINT EXAMPLE

The following equation describes the relationship between power through an aperture, Φ_f , to total power, Φ_o , of a circular, Gaussian laser beam, given the beam diameter at the 1/e power points, D_L , the aperture diameter, D_f , and neglecting atmospheric losses.¹

$$\frac{\Phi_f}{\Phi_o} = \left[1 - e^{-\left(\frac{D_f}{D_L}\right)^2} \right] \quad (2)$$

Given the total power and the power through an aperture at two points down range from a laser, equation 2 can be used to determine the 1/e beam diameters at each point down range. The divergence of the laser can then be calculated using the following equation

$$\phi = 2 \tan^{-1} \left(\frac{D_{L2} - D_{L1}}{2r_{2-1}} \right) \quad (3)$$

where D_{L1} is the calculated 1/e beam diameter at the first point, D_{L2} is the calculated 1/e beam diameter at the second point, and r_{2-1} is the distance between the two points.

The U. S. Navy two-person team used this method to measure the divergence of the lasers using a variable aperture, a caliper, a tape measure, and a hand-held meter and detector. At the Luxor Hotel, measurements were taken in the laser bunker and outdoors. At the Hilton, measurements were taken in a laser bunker, on a large carport roof, and in the fountain where the actual light show output exists. The measurement team using this method had no trouble performing measurements other than the fact that one of the team members had to don a set of hip waders and climb a ladder in the fountain to get a direct power measurement. However, this demonstrated the portability of this technique. Setup and measurement took ten to fifteen minutes at each hotel.

2.3.2 Long Focal Length Lens And Small Aperture Method

Measurements to determine the divergence of a laser using the long focal length lens and small aperture method require a long focal length lens, a set of fixed apertures or a variable aperture, an optical detector, and some means of aligning the lens, the aperture, and the detector (e.g., optical table or tripods). The lens must be large enough to collect the entire laser beam and must have a known focal length at the laser wavelength being measured. The setup for taking the measurement required is shown in Figure 3, where f is the focal length of the lens. Care must be taken to be sure of proper alignment for an accurate measurement. Typically, the aperture is in a fixture that uses a micrometer to move the aperture in the focal plane to maximize power to the detector.

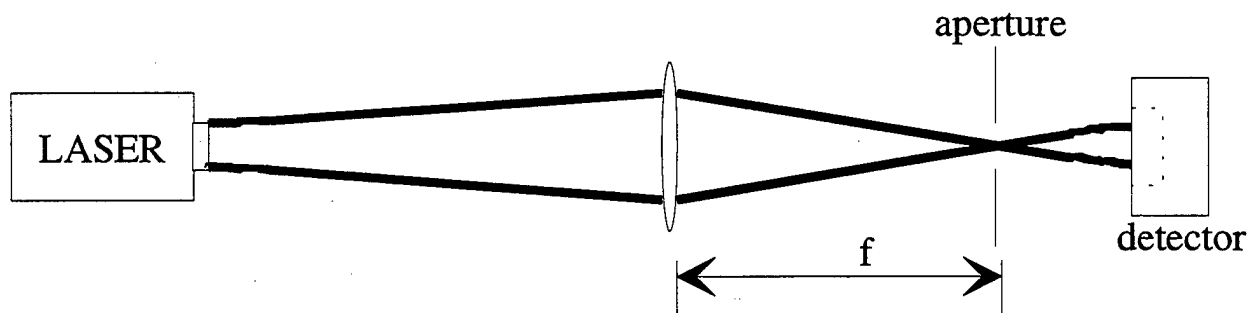


FIGURE 3. LONG FOCAL LENGTH LENS AND SMALL APERTURE METHOD SETUP

The size of an aperture that passes 63% of the total power is the 1/e beam diameter at the focal length of the lens, D_{fp} . Otherwise, D_{fp} must be calculated from the percentage of the total power transmitted by the aperture as follows²

$$D_{fp} = \sqrt{\frac{-d^2}{\ln \left[1 - \frac{\Phi_{fp}}{\Phi_0} \right]}} \quad (4)$$

where d is the aperture diameter, Φ_{fp} is the power transmitted through the aperture, and Φ_0 is the total power. The divergence of the laser can then be calculated using the following equation.

$$\phi = \frac{D_{fp}}{f} \quad (5)$$

The U. S. Army representative used this method to determine the divergence of the lasers using a long focal length lens, a set of fixed apertures, an optical detector, a tape measure, three tripods, and a power meter and detector. At the Luxor Hotel in the laser bunker on tripods the measurements worked well. At the Hilton, measurements were taken in the laser bunker, but could not be made on the carport roof. Setup and measurement took a less than one hour at each hotel.

2.3.3 Knife-Edge Technique

Measurements to determine the divergence of a laser using the knife-edge method³ require a focusing lens, a knife-edge with micrometer adjustment, an optical detector, and some means of aligning the lens, the knife-edge, and the detector (e.g., optical table or tripods). The setup is very similar to the long focal length lens method and is shown in Figure 4, where f is the focal length of the lens. The lens must be large enough to collect the entire beam and the focal length of the lens must be known very accurately to get a good measurement with this technique. The knife-edge is in a fixture that uses a micrometer to move the edge through the beam in the focal plane of the lens.

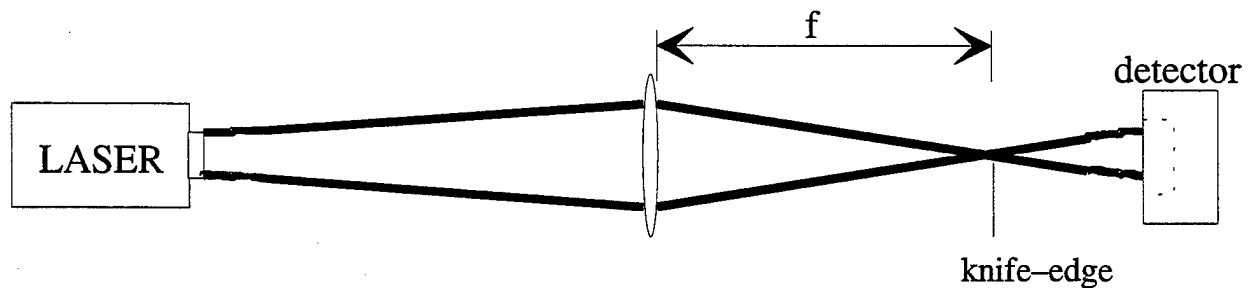


FIGURE 4. KNIFE-EDGE METHOD SETUP

At the focal length of the lens, f , the $1/e$ focused beam diameter, D_{fp} , is measured. The divergence of the laser can then be calculated using equation 5.

The U. S. Air Force group setup on a small optical table with a 12-cm diameter achromatic lens, a set of fold mirrors, a tape measure, a knife-edge, and a detector to make measurements to determine the divergence of the lasers. The optical table setup worked well in the laser bunker at the Luxor Hotel on a stable equipment table. However, at the Hilton, the platform measurements were being taken on was a large carport roof that vibrated with each step everyone took. The measurement team using this method had a very difficult time performing measurements on the carport and said that they had "very little confidence" in the measurement due to these vibrations. Also, measurement at the source in the fountain was impossible due to the lack of portability of the optical bench. Setup and measurement took one-and-a-half to two hours at each hotel.

2.3.4 Beam Profiler Method

Measurements to determine the divergence of a laser using this method may require a focusing lens, tape measure, optical detector, beam attenuation filters, beam profiling system, and some means of aligning the lens, filters, and beam profiling system. (e.g., optical table or tripods). Beam attenuator filters are usually needed to avoid saturation or destruction of the beam profiler camera. If a lens is needed, it must be of sufficient size to collect the entire laser beam. An accurate measurement is obtained when the spot size covers a large part of the active area of the camera. If the spot size is too small, this measurement can yield significant error. Due to the lack of portability, elaborate setup, and high cost, profilers are normally best suited for a laboratory environment.

The Walt Disney World representative demonstrated the beam profiler technique to determine beam divergence at the Luxor Hotel. Due to alignment difficulties, the divergence could not be obtained at either hotel.

SECTION 3

MEASUREMENT RESULTS

Overall, all techniques were in close agreement for the purposes of laser safety measurements. More time was spent on evaluation of the techniques once it was shown that all the techniques were accurate enough for laser safety measurements. It should be noted that manufacturer's specifications are sometimes design specifications, not actual values. For example, a divergence specification often means that the divergence is no greater than the specification given, and for laser safety, the minimum, not the maximum divergence is required. Table 1 gives the results of the respective measurements of each team at each hotel.

TABLE 1. MEASUREMENT RESULTS

Hotel	Light Show Manufacturer	Divergence (@ 1/e power points) (mrad)			
		Manufacturer Specified	Navy Two-Point Aperture	Army Long Focal Length Lens/Aperture	Air Force Knife-Edge
Hilton	Laser Fantasy	1.5	1.2	1.0	1.1
Hilton	Laser Fantasy	13	10.7	9.5	14.1
Luxor	Laser Media Skylight	0.4	0.23	0.29	0.38

3.1 COMPARISON OF TECHNIQUES

All the techniques have the accuracy required for laser safety measurements when the technique can feasibly be used. Each technique has certain limitations affecting how well it can be used to determine beam divergence of laser light show systems. Physical limitations are extremely important when attempting to make field measurements. For example, only the U. S. Navy team was able to make measurements in the fountain atop the Hilton's statue. Time may also be a factor since time required translates into a significant part of the cost of a method. An experienced technician with adequate training can perform the knife-edge measurement in a few hours,³ the long focal length lens small aperture measurement in one to two hours, or the two-point aperture measurement in a few minutes. The two-point aperture technique is fast and requires only a detector in the laser beam. Less time with the laser on and fewer reflective surfaces mean fewer chances for accidents to occur. For example, one observer was temporarily flashblinded while the knife-edge method was being set up on the carport roof at the Hilton several yards away. The two-point aperture method was considered by the majority of attendees and participants to be the simplest, quickest, and most practical technique for laser safety

measurement of laser light show beam divergence. Advantages and disadvantages of each technique are given in Table 2.

TABLE 2. ADVANTAGES AND DISADVANTAGES OF TECHNIQUES

Technique	Used by	Pros	Cons
Knife-edge with Focusing Lens	Air Force	Very accurate for laboratory measurements if the laser beam is Gaussian (and Circular if one-axis measurement) Requires little distance (usually 2 to 5 meters) Can be used with non-circular beams	Requires an Optical Table with several components Requires focusing the beam (can cause dangerous power densities) Takes a long time (a few hours) to set up and take measurements Not practical for many outdoor environments Requires advanced understanding of optics Requires expensive focusing lens and folding mirrors Equipment requirements high Requires a stable optical setup
Fixed Aperture with Focusing Lens	Army	Very accurate for laboratory measurements Requires little distance (usually 2 to 5 meters) Less complex than Knife-edge Technique	Requires focusing the beam (can cause dangerous power densities) Not practical for some outdoor environments Requires expensive focusing lens Requires advanced understanding of optics Requires a very stable optical setup Requires about an hour of setup and measurement time Cannot be used for non-circular beams without using other equations
Two-Point Aperture	Navy	Easy to perform measurements and calculations requiring little training Fast & convenient technique requiring only a few minutes for setup and laser-on time Fewer equipment requirements - fits in one case Portable setup No need for a stable platform means that one is able to work in a variety of environments (e.g., on a ladder) Safer technique due to fewer reflective surfaces and no need to focus the beam Can be done by one person Quickly and easily repeatable for double-check	Can require relatively long ranges to determine beam divergence for lasers with very large exit beam sizes or very small beam divergences (e.g., a 2-cm beam with a divergence of 0.5 mrad would require a range of 18 meters*) Range can be a problem, but with the portable property of this technique, this is rarely is so. (By comparison, a 5-mm beam with a divergence of 1-mrad can be measured in 2.3 meters*) Cannot be used for non-circular beams without using different equations
Beam Profiler	Walt Disney World	Very accurate technique Provides extra beam information Does not require a circular beam	Difficult to perform High training requirement Expensive equipment Not very portable Profiler camera is easily damaged

*assuming a 10% change in beam diameter between the measurement points

SECTION 4

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